OPTIMISATION OF A CRUCIFORM TEST SPECIMEN FOR BI-AXIAL LOADING OF FIBRE REINFORCED MATERIAL SYSTEMS

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1. INTRODUCTION

All too often, mechanical testing of fibre reinforced composites was (and still is) limited to uni-axially loaded specimens. In service however, fibre reinforced composites are hardly ever loaded in one direction. Experimental investigation of these materials should approximate real life behaviour as much as possible. In an attempt to achieve this goal bi-axial tests can be considered [1]. When bi-axial loads are applied, it is usually by superimposing a torsional load on tubular specimens subjected to tension or compression [2, 3]. Real construction components in fibre reinforced composite materials however, are often made in the form of flat or gently curved panels. Moreover, thin-walled tubes are not easy to fabricate and obtaining a perfect alignment and load introduction is not straightforward. Furthermore failure often occurs at the edge due to stress concentrations or local buckling [4, 5]. For this reason a bi-axial testing facility for planar cruciform specimens (Fig. 1) was developed at the Free University of Brussels.

2. PLANAR BI-AXIAL TESTING DEVICE

A bi-axial tension test bench for planar cruciform specimens with a maximum capacity of 100 kN is used. A successful bi-axial loading test satisfies two criteria: a test zone with a uniform bi-axial stress distribution should be obtained, and specimen failure must occur within this bi-axially loaded test zone —not in the uni-axially loaded arms. To fulfil the uniformity requirement, the force P has to be equal and co-linear to P' and the force F equal and co-linear to F' (Fig. 2). In addition P & P' has to be perpendicular to F & F'. As a consequence of such loading condition the center of the specimen will not undergo any displacement.

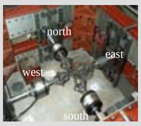

Fig. 1. Bi-axial test bench for flat cruciform specimens.

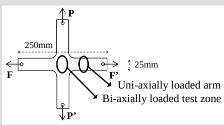

Fig. 2. Cruciform geometry with identification of forces.

3. CRUCIFORM SPECIMEN DESIGN

It has proven extremely difficult to develop a cruciform test specimen that simultaneously fulfils the following conditions: (i) there has to be a uniform strain state in the bi-axially loaded test zone, (ii) failure has to occur in the bi-axially loaded test zone and not in the uni-axially loaded arms, and (iii) the results should be repeatable [3, 5]. To investigate the influence of parameters like (i) the rounding radius at the intersection of the arms, (ii) the thickness of the bi-axially loaded test zone in relation to the thickness of the arms and (iii) the geometry of the bi-axially loaded test zone, finite element simulations were performed. Indicative isotropic simulations were performed to be able to perform a quick evaluation of the influence of certain parameters, and then orthotropic simulations were carried out with the complete lay-up modelled to investigate the influence of the directions of the fibres in the composite material. Afterwards, the numerical results were compared with experimental results obtained on selected cruciform geometries using digital image correlation for full field strain measurement. Strain gauges were also used as a reference to compare the obtained experimental strain results of this new technique.

3.1. Finite element simulations

Fig. 4 shows the finite element results of the first principal strains for three geometries A, B and C modelled as glass fibre reinforced epoxy with a $[(+45° \ -45° \ 0°)_4(+45° -45°)]$-lay-up (zone 2 on Fig. 4 with lay-up 2 on Fig. 3). In the middle of the specimens one layer of (0° +45° -45°) was milled away at each side of the specimen (zone 3) for geometries B and C. Due to symmetry, only one quarter is shown. The load ratio between the x- and y-directions was chosen equal to the strength ratio of both arms i.e. 3.85/1. The (+/-45°)-layers have a thickness of 0.61mm; the (0°)-layers of 0.88mm. The end-tabs are 2.5mm in thickness each (zone 1). The applied load was Fx/Fy = 46.2kN/12kN.

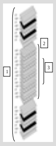

Fig. 3. Lay-up of specimens.

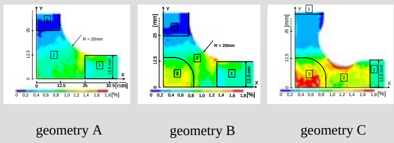

Fig. 4. Finite element results for three cruciform geometries. First principal strains are shown.

For geometry A, the first principal strains in the x-direction just beyond the end-tabs are higher than in the end-tabs, but are lower in the neighbourhood of the centre of the specimen. Consequently, failure of the specimen will occur close to the end-tabs. In order to increase the strains and the likelihood of failure in the bi-axially loaded zone, a reduction of the thickness and/or changing the rounding radius at the intersection of two perpendicular arms is necessary. In geometry B the first suggestion is shown. The strain results are improved; for this kind of geometry failure can occur at the middle of the specimen. If we use a combination of both suggestions, as shown in geometry C, even higher strains are obtained in the bi-axially loaded zone.

3.2. Experiments

a) Strain gauges

The experimental results for the three tested geometries A, B and C are shown in Table 1. Each value is an average of at least three experiments. Strain measurements were obtained in x- and y-direction by using rosette strain gauges glued in the centre of each specimen. The failure loads and failure strains were measured in both perpendicular directions. The failure stresses were calculated from the experimentally obtained failure strains using the stiffness moduli and Poisson's ratios measured on uni-axially loaded specimens. The highest failure strains are obtained for geometry C, indicating this geometry is the most promising one.

Table 1. Experimental results on three cruciform geometries.

	[kN]		[%]		[MPa]	
	F_x	F_y	ε_x	ε_y	σ_x	σ_y
geometry A	63,2	16,5	1,35	-0,56	395	14
geometry B	60,5	15,8	1,52	-0,66	442	13
geometry C	47,9	12,4	1,68	-0,79	516	56

For geometry A, failure of the specimen didn't occur in the bi-axially loaded test zone, whereas in geometries B and C it did (Fig. 5). These results confirm the results of the finite element simulations. The high values for the failure strains indicate that the strain concentrations at the rounding between the two arms in geometry C do not cause early failure of the specimen.

Fig. 5. Failure of cruciform specimen geometry C at 48.2kN. Failure occurs in the bi-axially loaded zone.

b) The digital image correlation technique

Digital image correlation (DIC) is a full field measurement technique that detects deformations using image processing. Once the deformations of a speckle pattern have been measured, the strain distribution in the material can be calculated [6]. This allows the uniformity of strains to be judged. The fundamental principle of this technique is based on the correspondence, for a large number of distinguishable small areas —known as macro image facets— between the distribution of grey scale values in the undeformed state and in the deformed state. In Fig. 6 the strain results obtained with the digital image correlation technique are compared with the finite element simulation results for geometry B. The pictures were taken immediately prior to failure.

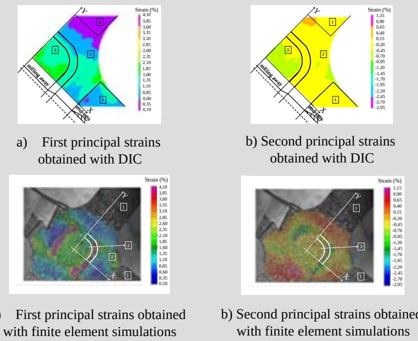

Fig. 6. Comparison between results of the digital image correlation technique and finite element simulations.

The results of the digital image correlation and the finite element simulations are substantially in agreement. Only in the transition zone between the full thickness and the milled area, high strains are observed with the digital image correlation technique. This may be due to the fact that only one camera was used, able to detect only in plane displacements on flat areas accurately.

4. CONCLUSIONS

The combination of finite element simulations and experiments performed on three different geometries of cruciform specimens, led to the selection of a suitable geometry for bi-axial testing of composite materials. This geometry has a reduced thickness in the central region, in combination with a rounding radius between two arms inside the material. These features cause failure to occur in the bi-axially loaded test zone. The strain values obtained with the digital image correlation technique are comparable with those measured using strain gauges and with those calculated in the finite element simulations. The strain distribution throughout the bi-axially loaded test zone can be considered as quite uniform.

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References

1. **Soden, P. D., Hinton, M. J., Kaddour A. S.,** "Predicting failure in composite laminates: the background to the exercise", *Composites Science and Technology*, **58**/7 (1998), 1001-1010.
2. **Soden, P. D., Hinton, M. J., Kaddour, A. S.,** "A comparison of the predictive capabilities of current failure theories for composite laminates", *Composites Science and Technology*, **58**/7 (1998), 1225-1254.
3. **Welsh, J. S.** and **Adams, D. F.,** "An experimental investigation of the biaxial strength of IM6/3501-6 carbon/epoxy cross-ply laminates using cruciform specimens", *Composites Part A: Applied Science and Manufacturing*, **33**/6 (2002), 829-839.
4. **Smith, E. W.** and **Pascoe, K. J.,** "Biaxial fatigue of a glass-fibre reinforced composite. Part 2: Failure criteria for fatigue and fracture", *Mechanical Engineering Publications*, London, Appendix 1.
5. **Dawicke, D. S.** and **Pollock, W. D.,** "Biaxial testing of 2219-T87 aluminum alloy using cruciform specimens", *NASA Contractor Report 4782*, (1997).
6. **Tyson J., Schmidt T., Galanulis K.**, "Advanced photogrammetry for robust deformation and strain measurement", *accepted for proceedings at SEM 2002 Annual conference*, Milwaukee, WI.